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TITLE: LOW TEMPERATURE DIFFUSION OF POSITIVE MUONS IN COPPER

MASTER

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LOW-TEMPERATURE DIFFUSION OF POSITIVE MUONS IN COPPER

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Abstract

Measurement of the depolarization of positive muons in copper in zero external field shows that the hopping rate of the muons increases as the temperature decreases from 4.2 K to ~ 1K. This is the first unambiguous demonstration of muon diffusion behavior which is <u>not</u> thermally activated.

We have recently completed a series of measurements on the diffusion behavior of positive muons (μ^+) in high purity copper targets in zero field as well as applied fields up to 80 Oe using the technique of muon spin rotation.(1) In these experiments a beam of polarized μ^+ extracted from the M9 meson channel at the TRIUMF accelerator in Vancouver, British Columbia, Canada was stopped in two different copper targets and one aluminum target. The muons thermalize in the target retaining their polarization and then depolarize under the influence of the local fields acting on them during their lifetimes (τ_μ = 2.197 μs). In our high purity targets (5 - 9's) these fields arise mainly from the copper nuclear moments. Since the angular distribution of the positrons is strongly correlated with the direction of the muon spin, a measurement of the positron distribution as a function of time determines the time dependence of the muon's spin direction. Since the nuclear spin - muon spin interaction is static and random in direction this leads to a smearing of the muon polarization as a function of time unless the muon is hopping rapidly. This is the same behavior as motional narrowing in NMR where the same formalism applies (2).

The impetus for our experiment was the result reported by Hartmann, et al. (3) on muon depolarization in high purity copper down to 50 mk in transverse field. Their data (Fig. 1) clearly shows a decrease in the depolarization rate as the temperature decreases from ~ 2K to ~ 0.7K. However, the transverse field data is not able to separate the static and dynamic effects i.e. it cannot distinguish whether there is a different trapping site appearing as a function of temperature or whether the muon is hopping more rapidly between identical sites.

In zero field, one can separate these effects. The mathematics of this approach has been worked out in detail in a recent paper by Hayano, et al. (4). Although the functional dependence of the muon spin's behavior cannot be given analytically, it can be calculated numerically for all values of Δ, the second moment of the Gaussian distribution of the static random magnetic fields and ν, the mean hopping frequency between sites.

The experiments were done on two different copper targets, one being a piece of the same target used in reference 3 and the other being a high purity single crystal annealed in low pressure oxygen to increase the residual resistivity ratio (5) as well as a 5 - 9's Al polycrystal to look for background effects. In order to reduce the number of variables to fit the zero field data as well as to compare our results with those of reference 3 we alternated zero field and transverse field runs.

A schematic plan view of the apparatus is shown in Fig. 2. The targets were attached to the rectangular cold box of the ^{3}He single shot evaporation refrigerator mounted in the pumped ^{4}He vapor space of a commercial Janis Supervaritemp dewar$^+$. Thermometry was done with a Ge resistance thermometer calibrated down to 0.3 K*.

Our transverse field results are plotted in Fig. 1 for the two different copper targets. The errors are smaller than the points and represent only the width of the χ^2 distribution. The agreement with the results of Ref. 3 is excellent.

The hopping rate in zero field is shown in Fig. 3. In the zero field data fits, the asymmetry for each telescope was taken from the average of all the asymmetries measured in the transverse field runs for that telescope. The width of the magnetic field distribution was fixed at $\Delta = .389\ \mu s^{-1}$. Thus only N_0, the initial counting rate, B, the time independent background and ν, the hopping rate were allowed to be varied in the least squares fits. The scatter in the data is large since ν depends greatly on the behavior of the

*Lakeshore Cryotronics, Westerville, Ohio, Model GR-200A-100
$^+$Janis Research Co. Inc., Stoneham, Mass.

muon polarization at very late times ($t > 2\tau_u$) when most of the muons have decayed, making it crucial to have a high muon event rate as well as a very "clean" spectrum. These somewhat mutually exclusive conditions can be attained on the unique M9 channel with particle separator at TRIUMF because of the very high intensity, positron-free surface muon beam. Each run represents 10^7 events collected over 6 hours counting time..

The diffusive behavior of muons in copper at temperatures from about 10 K to room temperature is now quite well understood (6) as a process wherein the muons jump between octahedral interstial sites via lattice-activated tunneling, with the muons becoming essentially completely trapped below about 80 K. We have shown that at temperatures far below that where this process is completely inhibited another mechanism of diffusion, one with a hopping rate decreasing with increasing temperature, becomes active. The experiments do not give any clear indication of what that mechanism may be, although the most obvious candidate which can yield such a non-classical temperature dependence is coherent tunnelling (7, 8). The evidence for the existence of this process in muon-metal systems is indirect, but it becomes more compelling as more data is accumulated which cannot be explained by thermally activated processes.

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Fig. 1 Second moment of the Gaussian width of the muon depolarization rate in transverse field. The second moment is defined in the same way as in Ref. 4. The Gaussian width parameters in Refs. 3 and 4 are formally related as $\sigma = \Delta/ 2$.

Data of Ref. 3 ▣ polycrystalline copper, 520 Oe
○ polycrystalline aluminum, 120 Oe
● polycrystalline aluminum, 520 Oe

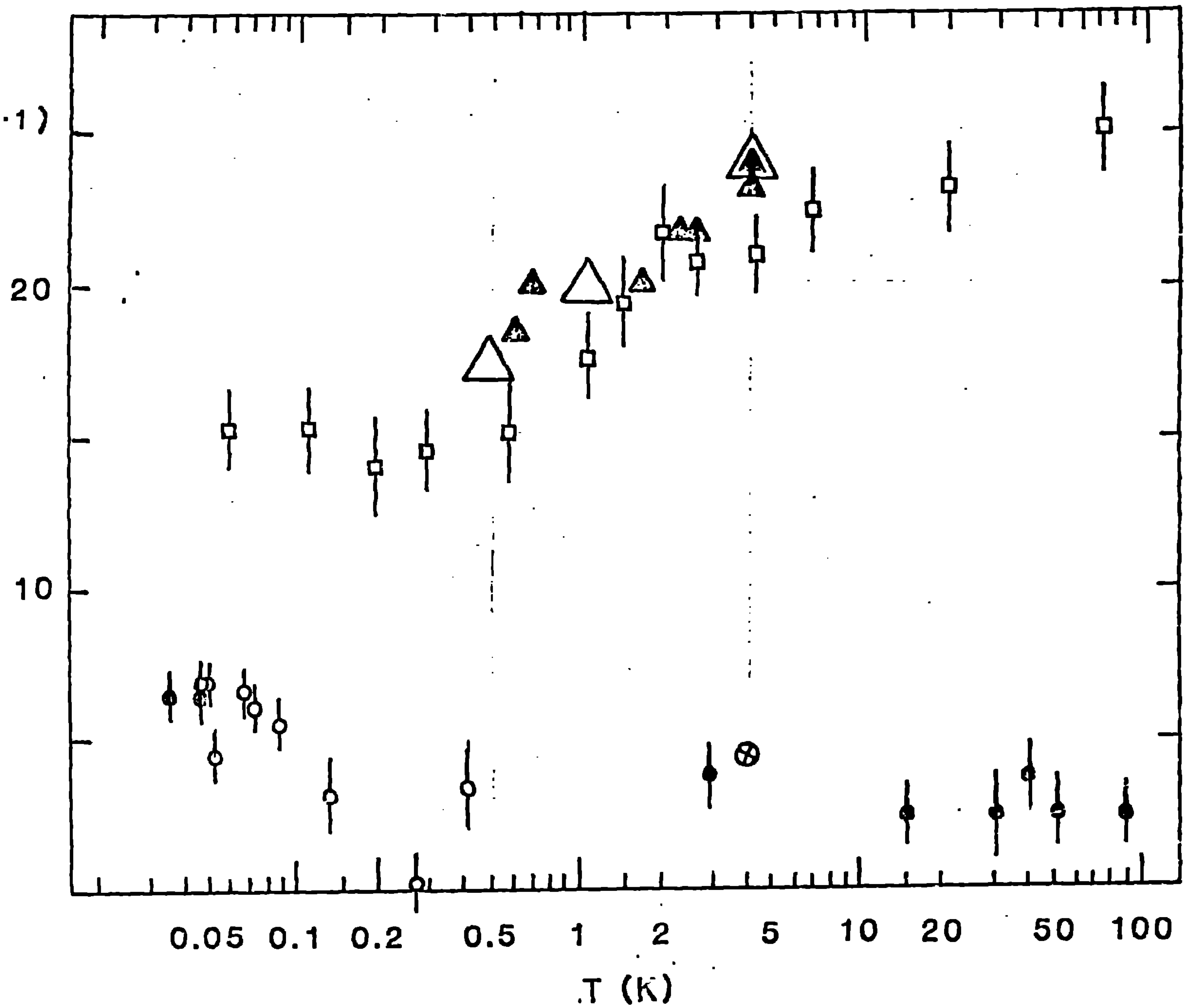
This work ▲ oxygen annealed high purity copper single crystal 80 Oe
Δ same copper target material as above, Ref. 3. 80 Oe
◉ high purity aluminum polycrystal, 80 Oe

Fig. 2 Schematic plan view of the spectrometer and low temperature refrigerator.

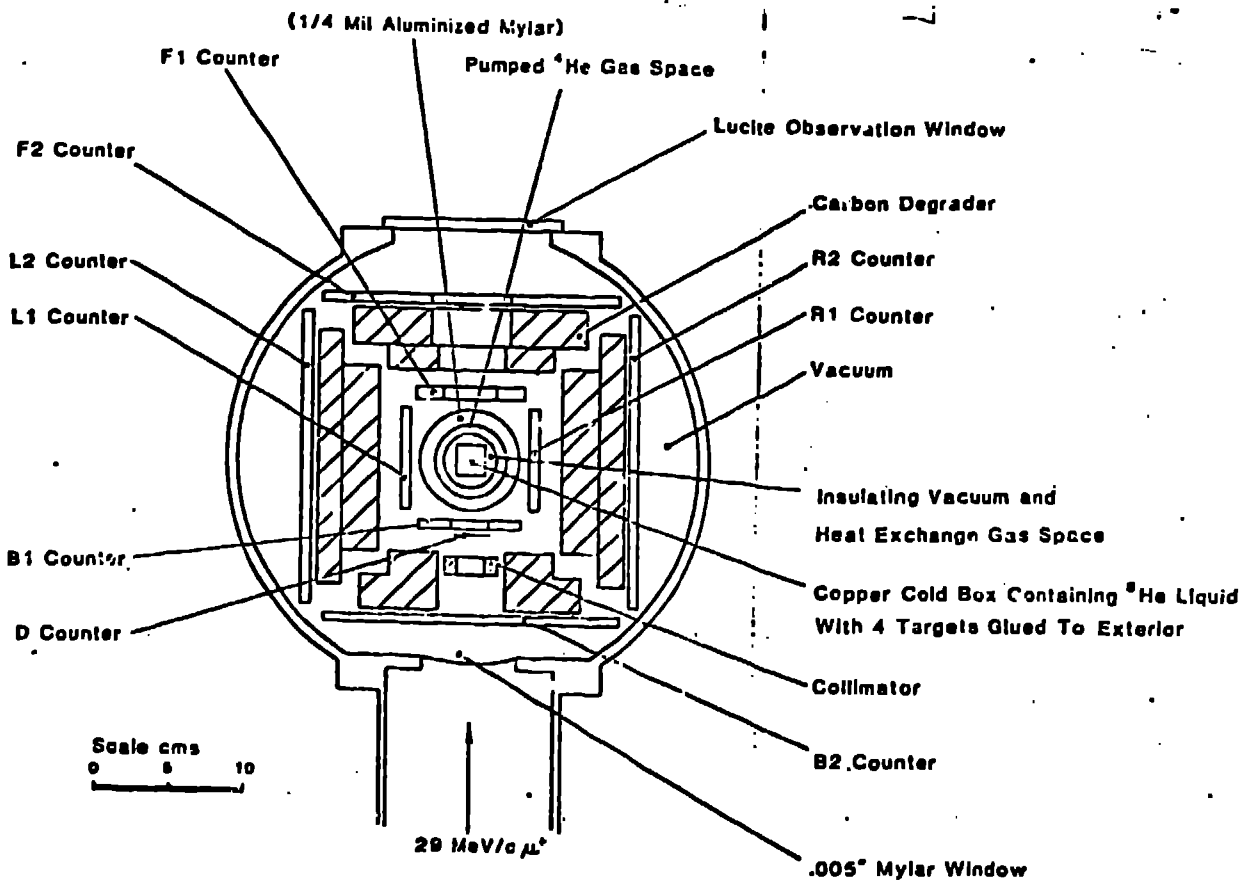
Fig. 3 Hopping rate of muons in copper in zero field

▲ oxygen annealed high purity copper single crystal
Δ same copper target material as Ref. 3

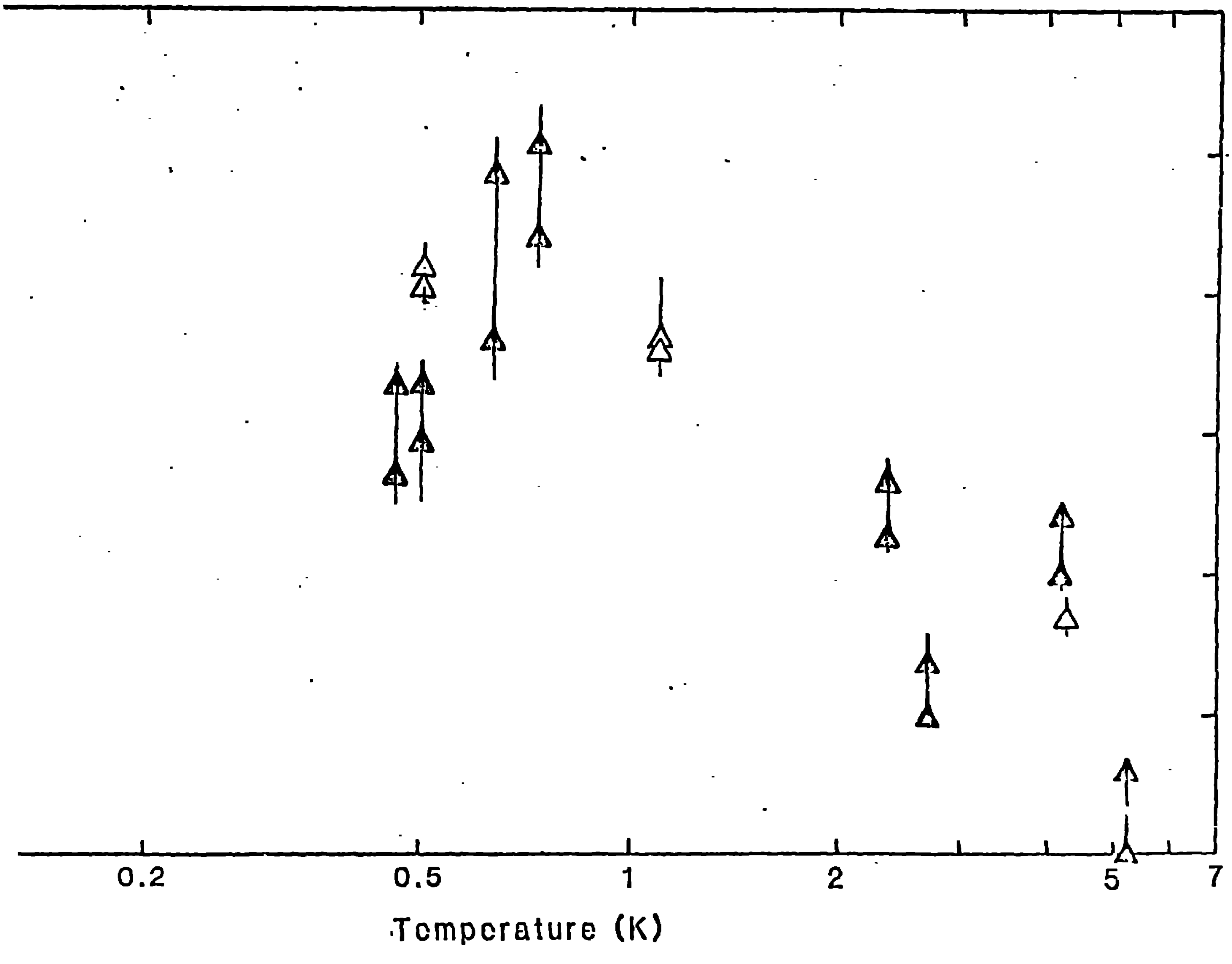
The data for F and B counters was analyzed independently and are connected by a vertical line. The errors from the 2 of the fits to the data are generally smaller than this spread and are indicated as error bars above the higher and below the lower point respectively.



·1)
20
10
0.05
0.1
0.2
0.5
1
2
5
10
20
50
100
T (K)



(1/4 Mil Aluminized Mylar)
F1 Counter
Pumped ^{4}He Gas Space
Lucite Observation Window
F2 Counter
Carbon Degrader
L2 Counter
R2 Counter
L1 Counter
R1 Counter
Vacuum
Insulating Vacuum and
Heat Exchange Gas Space
B1 Counter
Copper Cold Box Containing ^{3}He Liquid
With 4 Targets Glued To Exterior
D Counter
Collimator
Scale cms
0
5
10
B2 Counter
29 MeV/c μ^+
.005" Mylar Window


0.2
0.5
1
2
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7
Temperature (K)